Optical inclinometer   IAP20 Rec'd PCT/PTO 14 DEC 2005

The invention relates to an optical inclinometer
according to the precharacterizing clause of Claim 1, a
method for measuring the inclination of a device
according to the precharacterizing clause of Claim 13
and a geodetic device having such an inclinometer, a
method for compensating vibrations and/or random
fluctuations and a wavefront sensor for use in an
optical inclinometer according to the precharacterizing
clause of Claim 20.

Inclinometers of various designs have long been used in
all areas in which the position of a device is to be
taken into account. It is particularly true for
measurements in the geodetic area or in the building
trade.

In general, optical inclinometers of the generic type
and of the prior art are realized by positioning a
liquid surface in the pupil of an optical substance.
This liquid as a medium produces a phase shift of
radiation incident from a radiation source, it being
possible for the interaction of radiation and medium to
take place during reflection or transmission, and the
following relationships being applicable:

During reflection: $\phi = 2 \cdot P(x)$ (1)

During transmission: $\phi = (n-1) \cdot P(x)$ (2)

This parameter ϕ designates the phase shift, n

designates the refractive index of the liquid and *P(x)* designates the form function of the liquid surface, this being defined according to

5      $P(x) = 2\pi/\lambda \cdot x \cdot \cos(\alpha)$ (3)

and λ denoting the wavelength of the incident radiation, *x* denoting the lateral pupil coordinate and α denoting the angle of inclination relative to a
10   reference line.

The angle of the liquid surface relative to the reference line can be deduced according to equation (3) from the phase shift ϕ measured using apparatus.
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Patents DE 196 10 941 C2 and DE 198 19 610 C1 describe optical inclinometers of the generic type in which the change of direction of a light beam takes place as a reflection at an inclination-dependent surface of a
20   liquid. A structure is focused onto one- or two-dimensional sensor elements. The inclination is deduced from the change in the position of the image of the structure.

25   The Laid-Open Application DE 41 10 858 discloses a two-axis inclinometer in which a geometrical figure is projected onto a linear array by means of an inclination-sensitive and beam-deflecting sensor. The sensor contains a liquid, the position of which
30   relative to the device influences or deflects the projection of the figure on the linear array.

The International PCT Patent Application No.
PCT/EP03/05206 describes an optical inclinometer in
which a boundary layer between two media is focused
onto a camera. The inclination of a device equipped
5   with such an inclinometer is derived from the
parameters of this boundary layer, such as, for
example, the position and shape thereof.

In these inclinometers of the generic type, liquids are
10   used in which the inclination-dependent position of the
liquid surface is used indirectly or directly for
deriving the angle of inclination. However, the fact
that the use of a liquid surface is associated with a
multiplicity of problems which are due especially to
15   the dynamic properties of the liquid proves to be a
disadvantage. Thus, deviations of the surface from an
ideal plane are caused, for example, by vibrations or
by convection and lead to a corresponding effect on the
reflected or transmitted radiation.
20

As a result of these influences, various disturbances
of the wavefront occur. A random unevenness of the
liquid surface leads to a surface angle which varies as
a function of location and no longer permits the
25   acceptance of an angle of inclination α identical for
the entire liquid surface. Moreover, in the case of
accelerations of the medium or when thermal gradients
occur, deformations of the surface result which can be
modelled in principle as higher-order aspherical
30   aberrations but to date have not been taken into
account. As a result of such a disturbed surface, the
image of a structure on a sensor is distorted or
blurred or the contrast is reduced so that the

measurement is associated with difficulty.

Approaches to date for compensation relate, for example, to handling measures for directly reducing the effects, such as, for example, the introduction of dead times during which an inclinometer warms up after commissioning, or equipment designs, such as, for example, sufficiently large dimensioning of the liquid containers. In addition, the possible area of use of an inclinometer can be limited, for example with regard to the permissible vibration or acceleration.

The objects of the present invention consist in general in the improvement of an optical inclinometer of the generic type.

In particular, one object consists in the provision of an inclinometer which has improved accuracy of measurement.

Further objects consist in the further miniaturizability of an inclinometer of the generic type and in the simplification of its design.

A further object consists in the provision of an inclinometer in which limitations of use with regard to time, in particular owing to thermal effects, are reduced or avoided.

A further object of the invention is to provide an inclinometer which has an extended area of use compared with the prior art, in particular with regard to mechanical stress due to vibrations.

A further object consists in the provision of a method which permits disturbances of a wavefront in an inclinometer to be taken into account algorithmically or electronically.

A further object of the present invention consists in ensuring a constructional integratability in geodetic devices or devices used in the building industry. This relates in particular to the use of existing electronic components as evaluation devices.

A further object consists in the provision of a wavefront sensor for an inclinometer, which permits measurement in a greater angle range and/or has higher resolution and/or a greater dynamic range.

These objects are achieved, according to the invention, by characterizing features of Claims 1, 13 and 20, respectively, or by characterizing features of the subclaims.

The present invention relates to an optical inclinometer. The radiation source generates radiation by means of which a wavefront is focused by a medium, the position of which is inclination-dependent, onto a detector, it being possible for this detector to be a one-dimensional or multidimensional, in particular extensive, camera. The medium is held by a container. This container may consist, for example, of a can for holding a liquid. The imaging need not correspond to imaging in the optically exact sense. What is important is the transillumination of the container with at least one first medium present therein or held by said

container or the reflection of the radiation at a surface or boundary layer of this medium, after which detection of the wavefront takes place in such a way that inclination can be deduced from this.

The structure can be superposed externally on the radiation, for example by means of a shutter or a transmission or reflection code, or may consist of a structure inherent in the radiation. What is important is a structure of the radiation field, which structure, after interaction with the inclination-dependent medium, is changed in its imaging on the detector so that the position of the medium can be deduced from this change. The inclination is determined relative to a reference line which serves as a reference and which usually coincides with a reference parameter of a device, for example of a reticule or of an alignment edge.

The radiation used may be in the visible or in the nonvisible spectral range and is as a rule determined by the technical and physical parameters of radiation source, detector and medium. In addition to conventional lamps of various types, light emitting diodes or lasers, in particular semiconductor lasers, can also be used as the radiation source, it being possible to guide the radiation by optical elements, such as, for example, optical fibres, the manner advantageous with respect to the device. Depending on the form of realization, the medium is transilluminated by this radiation or the medium serves for reflecting the radiation.

Examples of liquids suitable as the medium are mercury, water and silicone oil. Both reflection at a boundary layer and passage through a medium or a combination of the two can be used for fixing the position of the medium.

The image of the structure is projected after this reflection and/or transmission onto the camera and is picked up there and converted into electronic signals. For example, a CCD camera or a CMOS camera may serve as a suitable camera. Such a camera is obtainable, for example, as CMOS monochromatic image sensor ADCS 2120 from Agilent, which has a field of 640 x 480 pixels.

The signals generated by the camera are analyzed by an evaluation unit and evaluated with respect to the inclination of the device. A separate building block or a separate component can be used for this purpose. Alternatively, however, it is also possible to rely on any existing components of other devices. In an inclinometer integrated in the telemeter, for example the function of this evaluation unit can also be performed by the electronics used for the distance measurement. Similarly, sources already used for other purposes can also be used as a radiation source. Thus, in the example of the telemeter, a part of the laser light optionally used there for the distance measurement can be output and, preferably after scattering or beam diversion, used for the imaging.

According to the invention, troublesome effects of the interaction of the radiation field with the medium are taken into account by an analysis of information about

the wavefront of the radiation, and the influence of a disturbed liquid surface thus compensated. Various suitable approaches for conversion by means of algorithm or circuit technology are available.

The illumination of the structure is advantageously effected by means of a plane or slightly spherical wave, which, however, after interaction with the medium, may have aberrations which may be caused, for example, by irregularities of the surface of the medium, but also by inhomogeneities in the interior of the medium, as are produced, for example, by convection. These disturbances of the surface or of the interior of the medium occur, for example, as a result of temperature gradients during the switch-on phase of the device or are superposed by external influences, such as, for example, vibrations. In order to keep these influences in a tolerable range, in inclinometers of the prior art the container dimensions are chosen to be sufficiently large so that miniaturization has to date encountered limits. A supplementary or alternative measure is the acceptance of dead times of the inclinometer, during which a transient process or compensation process takes place and the accuracy of measurement is limited.

An inclinometer according to the invention uses a detector which is in the form of a wavefront sensor or has a wavefront sensor for deriving information about the wavefront. Detector and wavefront sensor can advantageously be arranged directly after the medium. In order to avoid further impairments of the imaging quality, it is additionally advantageous, when

transilluminating the medium, to choose the beam path which is perpendicular to the surface of the medium and, after leaving the medium, strikes the wavefront sensor directly.

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An example of a suitable wavefront sensor is a Shack-Hartmann wavefront sensor (SHS), although, according to the invention, in principle other types of sensors can also be used. A Shack-Hartmann wavefront

10   sensor has a microlens array, by means of which a multiplicity of subapertures is formed. These microlenses may be arranged both purely in the form of rows and therefore linearly and in the form of a matrix and hence extensively. By a suitable choice of focal

15   distances of the microlens array, it is possible to establish a sufficiently high angle resolution. With an adequate knowledge of the wavefront, troublesome aberrations of the wavefront can be eliminated by calibration. In general, the lenses are used

20   equidistant in a two-dimensional lateral arrangement, a matrix of focal points being generated. The shift of each focal point on the axis of the lens is a measure of the tilt of the wavefront within the aperture of this lens. With suitable algorithms, the entire

25   wavefront can be approximately reconstructed from the sum of the focal points. By scanning the wavefront with the many subapertures, a substantial or complete reconstruction of the topography of the surface of the oil or of the wavefront can be effected, or only a part

30   of the information can be used, for example for selecting image points of the detector with undistorted imaging.

CCD and CMOS sensors can be used for detecting the position of the focal point, an array of at least 2 x 2 pixels being used for each subaperture. In this design, this corresponds to a quadrant sensor. Depending on the required resolution, however, it is also possible to use larger numbers of pixels per subaperture. For increasing the read-out speed and for reducing the noise, a combination to give superstructures of pixels is realizable. The use of purely linear wavefront sensors arranged in rows is also suitable.

By using a wavefront sensor, it is also possible to reduce the complexity of apparatus since no 4f optical system may be used and the microlens arrays can be easily and economically produced by replica methods.

The wavefront sensor provides information about parameters or the shape of the wavefront, which information can be used algorithmically or by means of circuit technology for compensating the aberrations. Firstly, the wavefront can be completely or partly analyzed with regard to its form function. In general, a wavefront $W(x,y)$ can be approximated by a sum of higher-order polynomials. A possible derivation is possible, for example, with the aid of Zernike polynomials. A wavefront $W(x,y)$ is represented as the sum

$$W(x,y) = \sum_{0}^{\infty} C_n Z_n(x,y) \tag{4}$$

with the coefficient C_n, where the first ten polynomials

$Z_n(x,y)$ can be defined in Cartesian coordinates as follows

$$Z_1(x,y) = y$$
$$Z_2(x,y) = x$$
$$Z_3(x,y) = -x^2 + y^2$$
$$Z_4(x,y) = 2xy$$
$$Z_5(x,y) = -1 + 2x^2 + 2y^2$$
$$Z_6(x,y) = -3x^2y + y^3 \qquad\qquad (5)$$
$$Z_7(x,y) = -x^3 + 3xy^2$$
$$Z_8(x,y) = -2y + 3x^2y + 3y^3$$
$$Z_9(x,y) = -2x + 3x^3 + 3xy^2$$
$$Z_{10}(x,y) = x^4 - 6x^2y^2 + y^4$$

Here, corresponding coefficients can also be assigned to special optical errors, such as, for example, Z_5 with respect to astigmatism.

In addition to the reconstruction of the wavefront, straightforward recognition of pixels is also possible, the coordinated aperture of which detects a flat section or a portion of the wavefront without tilt or disturbance. It is thus possible to ensure that only the content of such pixels is used for an evaluation and the faults are eliminated very close to the hardware.

In addition, the local information about the shape of the wavefront can also be correlated. Suitable algorithms, for example for wavelet transformation, which permit, for example, a reduction of the noise, are also available.

For increasing the performance characteristics of an
optical inclinometer according to the invention, a
wavefront sensor according to the invention can be
used. In this wavefront sensor according to the
5   invention, its resolution and absolute determination of
the wavefront is increased by unique assignment of the
wavefront sections. Wavefront sensors according to the
Shack-Hartmann principle of the prior art use only the
position determination of the focal point within the
10   respective subaperture. The resolution is thus limited
by the focal distance of the individual microlenses and
the number of microlenses and the image points
coordinated in each case with a microlens. Furthermore,
no absolute determination of the wavefront is possible
15   without modification of the microlens arrays, owing to
the dark spots. In the wavefront sensor according to
the invention, a diffractive element is introduced
before the microlenses, by means of which element it is
ensured that, instead of a focal point in the
20   subaperture, a plurality of focal points of the
diffraction orders generated or whole diffraction
images are used for determining the exact wavefront. It
is possible to utilize the fact that, in addition to
the image points coordinated in each case with a
25   microlens, further image points of the detector are
also illuminated. Separation and coordination of the
illuminated structures with the respective subapertures
can be realized by an algorithmic route by methods
known per se. A readily distinguishable form of the
30   diffraction structures, as can be realized, for
example, by large intensity changes, for example as in
the case of a bar code, is advantageous, it also being
possible to take into account according to the

invention, properties particularly suitable for code reconstruction, such as, for example, the use of an M-sequence.

5   By means of the method according to the invention or the device according to the invention, the transient phase after the device has been switched on can be shortened. It is also possible to reduce the dimensions of the container for the medium so that the
10   inclinometer is further miniaturizable.

The method according to the invention and a device according to the invention are described in more detail below purely by way of example with reference to
15   working examples shown schematically in the drawing. Specifically,

Fig. 1a-b   show the schematic diagram of an inclinometer with reflection according to
20   the prior art;

Fig. 2   shows the schematic diagram of an inclinometer with transmission according to the prior art;

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Fig. 3a-b   show the schematic diagram of the arrangement and effect, according to the invention, of a wavefront sensor;

30   Fig. 4   shows the schematic diagram of the use, according to the invention, of a wavefront sensor;

Fig. 5   shows the schematic diagram of a first
              embodiment of an inclinometer according to
              the invention in side view;

Fig. 6   shows the schematic diagram of a second
              embodiment of an inclinometer according to
              the invention in side view;

Fig. 7a-b   show the schematic diagram of a third
              embodiment of an inclinometer according to
              the invention in side and plan view;

Fig. 8   shows a schematic diagram of a form of the
              method according to the invention; and

Fig. 9   shows the schematic diagram of a wavefront
              sensor according to the invention.

Fig. 1a-b describe an inclinometer according to the
prior art which operates according to the reflection
principle. Fig. 1a shows the condition in the case of a
horizontal orientation of the inclinometer, whereas
Fig. 1b shows the condition in the case of a slight
inclination. In Fig. 1a, radiation S emitted by a
radiation source is incident on a bar code as structure
1 to be imaged and is fed into a prism body 2,
reflected there at an inner surface and reflected onto
a liquid layer 4 present on the surface of the prism
body 2. Further reflection at that surface of the
liquid layer 4 which faces away from the prism body 2
and subsequent focusing onto a detector 3 take place,
which detector 3 is formed here by way of example as a
linear array. The structure 1 is focused on the

detector 3 as an image B. The position of the image B
is dependent on the angle of that surface of the liquid
layer 4 which faces away from the prism body 2 relative
to the prism body 2.

Fig. 1b shows a situation which is similar to Fig. 1a
and in which the liquid layer 4 acquires a wedge-shaped
cross-section owing to the inclination. As a result of
this, the surfaces of the liquid layer 4 which face the
prism body 2 and face away therefrom are no longer
parallel but are present at an angle to one another.
The radiation S reflected at the inner surface of the
prism body now strikes a surface of the liquid layer 4
inclined differently compared with Fig. 1a and is thus
projected at a different angle onto the detector 3. The
image B of the bar code as structure 1 thus also
shifts. The inclination can be deduced from the extent
of the shift of the image B.

Fig. 2 schematically shows an inclinometer with
transmission according to the prior art. A bar code as
structure 1 is fed via an optical system comprising at
least one collimating lens 5' through a medium 6 and is
focused by means of an optical system comprising at
least one focusing lens 5'' onto a detector not shown
explicitly here. The wavefront WF1 which is still flat
or slightly spherical but undisturbed after passage
through the transmittive bar code undergoes a change in
its shape due to irregularities of the surface or
inhomogeneities within the disturbed medium 6, so that
a disturbed wavefront WF2 results. This change of the
undisturbed wavefront WF1 into a disturbed wavefront
WF2 leads to a likewise disturbed image B' on the

detector. For example, the contrast in the structure 1 may be reduced by these influences so that the differentiation of individual features of the structure 1 is complicated or adversely affected.

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The arrangement and effect, according to the invention, of a wavefront sensor is explained schematically in Fig. 3a-b, Fig. 3a illustrating the situation with an undisturbed medium 6' and Fig. 3b that with a disturbed

10   medium 6.

In Fig. 3a, the radiation is incident on an undisturbed medium 6' and passes through it, passage taking place substantially perpendicularly to the surface in order

15   to reduce losses and aberrations. After the passage, the wavefront WF3 is undisturbed and substantially flat. When the radiation strikes the wavefront sensor, which has a multiplicity of microlenses 7 having coordinated subapertures, the radiation of each

20   subaperture is focused onto a camera 8. Since the wavefront WF3 is flat, it has the same parallel course everywhere and hence identical angle relative to the wavefront sensor, so that the focal points FP on the camera 8 are equidistant and are produced on the

25   optical axis of each microlens 7.

Fig. 3b shows the situation for a disturbed wavefront WF4 which, after passage through the disturbed medium 6, has aberrations and hence a course which is no

30   longer flat. The microlenses 7 in turn project the radiation captured by their respective subaperture onto the detector 8. Since the angle of the captured wavefront section is now locally different for each of

these subapertures, the associated focal points FP also have different spacings. In the case of the subapertures which capture a non-parallel wavefront section, focal point FP and optical axis no longer

5   coincide so that a deviation results. Since that region of the camera 8 which is coordinated with a subaperture has a plurality of pixels, the position of the focal point FP can be resolved and the angle of the wavefront section can therefore be deduced.

10

These conditions are illustrated once again in Fig. 4, and the parameters derivable for use according to the invention are schematically shown. The wavefront section captured by the subapertures of the individual

15   microlenses 7 is focused onto the camera 8, it being possible for focal point SP and optical axis OA to coincide or to be separated depending on the specific course. For example, a focal point FP to the left of the optical axis OA (in this example) indicates

20   radiation incident from the right, so that a corresponding inclination of the respective wavefront section can be derived. The extent of the separation of the focal point FP and optical axis OA is a function of the angle of the wavefront section.

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Fig. 5 shows a first embodiment of an optical inclinometer according to the invention. An oblique, reflective surface of the housing of an inclinometer according to the invention is illuminated by the

30   radiation S fed into an optical fibre as local radiation source 11. The detector 3' has a wavefront sensor with a camera 8' and an upstream array of microlenses 7. An evaluation unit 9' is positioned on

that side of the camera 8' which is opposite the incident radiation. By means of such an arrangement of the components, a particularly flat design of the inclinometer can be realized.

Fig. 6 schematically shows a second embodiment of an optical inclinometer according to the invention, with integration of all components on a plate as common base 12, in side view. Visible or invisible radiation S is emitted perpendicularly to the base 12 by a radiation source 11'. The radiation S is collimated by a lens 5''' and again deflected by means of a first deflection element 13' and a second deflection element 13'' so that it is incident perpendicularly to the base 1. In the region of the incident radiation, a container for the medium 6' having a first surface oriented relative to the base and a second surface oriented relative to the second deflection element 13'' is mounted on the base 1. A detector 3'' having a wavefront sensor comprising a camera 8'' and an upstream array of microlenses 7 is present between base 12 and the container or the first surface thereof. The detector 3'' is connected to an evaluation unit 9''. In order to save space, the components belonging to the beam generation, to the beam path and to the beam reception are mounted on one side of the base 12, but the evaluation unit 9'' on the opposite side of the base 12, but in principle a different arrangement of the components or of the evaluation unit 9'' can also be chosen. This arrangement therefore has the advantage of the integration of all electronic components on a common base 12, which, for example, may also be in the form of a circuit board. This makes it possible to

realize a simple and mechanically sensitive setup. The deflection elements 13' and 13'' may be in the form of reflective components, for example in the form of prisms or mirrors. In principle, if mounting on a

5   common base 12 is dispensed with, however, direct mounting of the components one on top of the other is also possible, as shown in a second embodiment according to the invention in Fig. 5 or Fig. 7a-b.

10   Fig. 7a-b shows a third embodiment of an optical inclinometer according to the invention with coaxial arrangement of all components. The base 12' is substantially U-shaped and holds a radiation source 11'' between the two limbs. The radiation source emits

15   radiation S, which is collimated by a lens 5'''. The collimated radiation S is then fed through the medium 6', which is mounted in a container indirectly or directly on the detector 3''' which has a wavefront sensor with a camera 8''' and microlenses 7 arranged in

20   an extensive manner. An evaluation unit 9''' is mounted on that side of the base 12' which is opposite the detector 3'''.

Fig. 7b shows a plan view of the arrangement of the
25   microlenses 7 of a wavefront sensor in a third embodiment of an inclinometer according to the invention, in which the radiation source, lens and container with the medium were omitted in the diagram. Here, the radiation is focused by means of the
30   microlenses 7 arranged in an extensive manner onto the camera 8''' of the detector.

A possible form of the method according to the

invention is explained schematically in Fig. 8. In the
case of a detector setup, according to the principle
explained in Fig. 4 with wavefront sensor, the
individual pixels of the camera 8 are included in the
5   evaluation only when the focal point FP1 coincides with
the optical axis OA of the respective microlens 7 or
the deviation thereof from one another is within a
specified tolerance. Only the pixels which satisfy this
condition are then read out or further processed for
10   the evaluation, so that only that part of the image
which can be received without aberration is used. It is
also possible to correlate different pixels with one
another; in particular, pixels can be combined to form
larger superstructures. Furthermore, image processing
15   methods known per se can be applied to the image thus
obtained, in order to obtain an improvement in the
optical parameters.

Fig. 9 schematically shows an embodiment of the
20   wavefront sensor according to the invention. Arranged
in front of the microlenses 7 is a diffractive element
14 by means of which the radiation arriving from the
wavefront WF4 is diffracted. This diffractive element
may be, for example, a hologram, a grating, in
25   particular a Dammann grating, or another optical-
gradient structure. In addition to the direct
positioning above the microlenses 7, mounting at
another point in the beam path, for example on one of
the deflection mirrors of Fig. 6 or in the immediate
30   vicinity of the medium, for example on a glass of the
container, is also possible. The diffraction effect
produces on the camera 8 a plurality of intensity
structures 15 which are correlated with one another,

instead of or in addition to the undisturbed focal point FP2. Depending on the design of the diffractive element 14 and the shape of the wavefront WF4, these structures can also be imaged in regions which, in the

5   case of a wavefront sensor without diffractive element 14, would in each case have been assigned exclusively to another subaperture. In addition to the higher diffraction orders, these structures may also be, for example, expanded Fourier images of the diffractive

10   element. It is thus possible, for each subaperture, to use a larger region of the camera 8 for detection and thus to achieve a higher resolution, larger detectable angle ranges and/or a larger dynamic region.

15   The embodiments shown represent only examples of realizations according to the invention and are therefore not to be understood as being definitive and limiting. In addition, the person skilled in the art can derive further embodiments according to the

20   invention, for example with the use of other beam paths or deflection elements, such as, for example, prisms, scattering surfaces or optical fibres, or alternative forms of the detector and of the wavefront sensor.

25   The figures show the lenses of the wavefront sensor and in particular the number and size thereof purely schematically. In the real embodiments, the number of lenses is generally greater so that higher resolutions of the position or angle can be realized.

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